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Assessing Natural and Mechanical Dune Performance in a Post-Hurricane Environment

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Abstract: The purpose of this study is to document the geomorphic evolution of a mechanical dune over approximately one year following its installation and compare it to the recovery of a natural dune following the impact of Hurricane Matthew (2016). During the study period, the dunes' integrity was tested by wave and wind events, including king tides, and a second hurricane (Irma, 2017), at the end of the study period. Prior to the impact of the second hurricane, the volumetric increase of the mechanical and natural dune was 32% and 75%, respectively, suggesting that scraping alone is not the optimal protection method. If scraping is employed, we advocate that the dune should be augmented by planting. Ideally, the storm-impacted dune should naturally recover. Post-storm vegetation regrowth was lower around the mechanical dune, which encouraged aeolian transport and dune deflation. Hurricane Irma, an extreme forcing event, substantially impacted the dunes. The natural dune was scarped and the mechanical dune was overtopped; the system was essentially left homogeneous following the hurricane. The results from this study question the current practice of sand scraping along the South Carolina coast, which occurs post-storm, emplacement along the former primary dune line, and does not include the planting of vegetation.

Keywords: coastal stabilization; dune recovery; hurricane impact; aeolian geomorphology; beach scraping

1. Introduction

Increasing storm frequency and growing populations along the coastal zone force coastal zone managers to intricately balance nature and society. When storms threaten to devastate this region, action must be taken to protect coastal infrastructure and life. Beach scraping is one such method employed after storms where nearshore sand is artificially transported to create a berm or a dune-like landform. This is a common practice along the U.S. East Coast [1]. Especially in South Carolina, it is believed that scraping protects coastal infrastructure from near-term high tide and king tide flooding events occurring shortly after substantial storms [2]. King tides are naturally-occurring elevated water levels that South Carolina has defined as meeting or exceeding 6.6 ft (2.0 m) at the Charleston Harbor tide gauge [3]. Following the hurricanes impacting the community of Isle of Palms, SC, scraped sand is placed along the former primary dune line. Here we describe the ~10 month evolution of these scraped (herein mechanical) dunes compared to the recovery of natural dunes following a hurricane and several mid-latitude cyclones. We also present the morphological changes after a hurricane impact (Irma) that impacted the system approximately 10 months after emplacement of the mechanical dune. The results from this study question the effectiveness of the current practice of post-storm sand scraping along the South Carolina coast, which is emplaced along the former primary dune line and does not include the planting of vegetation.

Beach-dune systems provide a natural defense against coastal storms. The level of protection offered by these dunes is related to their size and their ability to withstand the threat of wind and wave attack [4]. Unfortunately, in many coastal locations, the size and extent of natural dune systems have

been reduced, as coastal infrastructure expands [5]. In developed areas, alternative dune building strategies must be employed to counteract the effects of diminishing natural coastal land space [4].

Beach scraping is a soft engineering technique that is not part of the beach nourishment framework because no new sediment is introduced into the system [6]. During scraping, sand is redistributed within the beach-dune system, which artificially disrupts the beach and dune sediment budgets and the long-term environmental resilience of the beach-dune system ([7]; c.f., [8] for a comprehensive review of beach-dune interactions). For example, from a biological perspective, [9] found a decline of ghost crabs for 6–8 months after a beach face was bulldozed for scraping. Figure 1a shows sand being scraped from the nearshore, which was eventually placed along the former primary dune line, which is shown in Figure 1b.



Figure 1. Sand scraping along the Isle of Palms, SC where (a) shows the sand source in nearshore and (b) shows the emplacement of the sand along the former primary dune line.

The short-term geomorphic impacts of scraping to the beach-dune system are moderately well-documented, however, it is not well understood whether the source beach experiences any morphologic impacts from scraping [1] or whether or not the profile gradient is steepened [10,11]. The immediate post-construction morphology of a mechanical dune is substantially different from a natural dune. The mechanical dune also has poor internal stratification [12] and the sand is more poorly sorted, compared to natural dunes [13], which is expected because the sand source is the beach. While this may not seem critical, previous work suggests that a relationship exists between aeolian sediment transport rates and sediment sorting [14]. [13] found higher rates of sediment transport on scraped dunes, compared to natural dune surfaces, and that the remaining deposits on the scraped surfaces were coarser. Sediment transport rates also depend upon the dune shape. Computational fluid dynamic (CFD) modeling of scraped dunes revealed that a dyke structure (or inverted “U”-shaped dune) experiences the most sediment transport, which will inhibit dune recovery [15]. This is notable because it is the evolutionary shape of the typical (to the South Carolina coast) inverted “V”-shaped mechanical dune.

Several studies have investigated the physical aspects of beach scraping, but the findings are inconsistent. These previous studies that were conducted along the U.S. East Coast from Maryland to Florida range in duration from 15 months (with 10 surveys of Myrtle Beach, SC; [16]) to one day (immediately post-storm; [17]). [1] conducted bi-weekly studies for one year at Topsail Beach, NC during a period that included Hurricane Hugo and found that the scraped dunes were “ineffective” during Hurricane Hugo. The scraped dunes lost almost 19 times more sand per m^3/m than the control (or natural) dunes [1]. It was suggested that the scraped beaches are disadvantaged because of the lack of vegetation, which anchors the sediment and reduces aeolian sand transport rates [1]. Interestingly, in the longest and most comprehensive previous study, [16] concluded that scraping provided little to no benefit if the shoreline is severely eroding; however, it remains a preferable technique to armoring. [17] also concluded that natural dunes served in a higher protective capacity in an immediate post-storm survey of the North Carolina coast following Hurricane Ginger. These post-storm

findings were replicated following Hurricane Hugo by [18] because the natural dunes were higher and vegetated.

Scraping is often considered a “temporary” measure [1] and one that, in South Carolina, may prevent damage from immediate storms and/or king tides [19]. Along the coast of South Carolina, it has been practiced frequently after substantial storms, including Hurricanes Hugo and Matthew. However, beach scraping on narrow beaches is considered to have “little restoration potential” [19]. ‘Restoration’ is a longer-term process and a key tenant of the Coastal Tidelands and Wetlands Act (as amended, S.C. Code Ann. §48-39-250 et seq. or, more commonly called, the SC Beachfront Management Act). This Act codifies the importance of the beach-dune system in managing coastal resources and specific activities that ensure dune restoration. Providing data on the impact of beach scraping on the beach-dune system is critical to the management process.

The South Carolina beach-dune system experienced substantial destruction during Hurricane Matthew in October 2016. Under natural conditions following a significant storm, dune sand is washed offshore to the bars and the bar sand expediently repositions to the beach. Over time, the accreted sand moves shoreward, repairing the beach profile. Foredunes then reappear with adequate sand and anchoring vegetation. Along portions of the South Carolina coast, beach scraping took place immediately after Hurricane Matthew as a mitigation effort to protect against the king tide flooding expected the following week. Scraping removes the sand from the beach foreshore to create a shore parallel sand pile (or what we call a ‘mechanical dune’), but it is not clear whether residents or tourists understand the full implications of such mitigation actions or their ‘effectiveness’ in protecting property.

Beach scraping in South Carolina is well regulated. Emergency orders must be issued from the South Carolina Department of Health and Environmental Control, Ocean & Coastal Resource Management (SCDHEC-OCRM) or an authorized official from the municipality, county, or the state to construct “temporary barriers against wave uprush” (S.C. Code Ann. Regs. 30-15.H). Sand scraping may be conducted to protect public health and safety if a structure is in danger and emergency conditions are imminent. While there are many specific logistics to scraping, most relevant to this research is that “sand may be placed against an eroded scarp or to replace an eroded dune that is seaward of a threatened structure” (S.C. Code Ann. Regs. 30-15.H(4)). The structure shall not exceed six feet above grade or 20 feet in width as measured from dune toe to dune toe” (S.C. Code Ann Regs. 30-15.H(4)(d)). The Blue Ribbon Committee on Shoreline Management Final Report documented 116 emergency orders in SC from 1985 to the time of the report’s publication [20]. They note that “... the number of issued emergency orders has steadily increased and may continue to do so if storms become more frequent and funding for renourishment is reduced or becomes more intermittent” [20] (p. 13).

It is evident that South Carolina law encourages beach scraping to create mechanical dunes. However, previous research, introduced above, suggests that these mechanical dunes do not perform well compared to their natural counterparts.

2. Materials and Methods

2.1. Study Area

The Isle of Palms is located 24 miles SSE of Charleston, SC. It is a 15.6 km long barrier island that is 427-975 meters wide [21]. It is a beach-ridge drumstick barrier island [22] with a monthly mesotidal range of 1.8-2.1 m. Island-wide modeling reports that the southwestern end of the island, which includes our field site, has minimal wave energy and a long-term accretionary trend [23]. Approximately 30 years ago, the southwest end of the island had the highest accretion rate on the island [2].

Inlet dynamics impact the erosion-accretion dynamics of the Isle of Palms. Most relevant to our study area (Figure 2) is the southwest extent of the island, which is bordered by the Breach Inlet. This inlet has an ebb-tidal delta that has experienced multiple-scale shoal-bypassing events [24]. During the smaller events, shoals detach from the delta, migrate towards the southwest, and attach to the

northeast end of Sullivan's Island [24]. Breach Inlet lost a considerable volume of sand from Hurricane Hugo [2]. During Hurricane Matthew, 96,930 m³ of sand was lost island-wide. However, the areas near Breach Inlet had net volumetric gains from substantial accretion of the nearshore bar and dune erosion [25]. During Hurricane Irma, 164,775 m³ was lost; this measurement only considered the northeast region of the island [26]. The area near Breach Inlet lost 7% of its volume [26].



Figure 2. Aerial image showing the southwest tip of the Isle of Palms, SC. Yellow and red rectangles highlight the location of the natural and mechanical dunes, respectively. Inset shows the entire Isle of Palms where the star is the southwest tip of the island shown in the larger figure.

The Isle of Palms has been influenced by an average of 1.6 tropical cyclones per year over the last century [27]. The most substantial historical hurricane is Hugo (1989), which was a Category 4 storm that resulted in 31.4 m³/m of erosion [2] along the Isle of Palms. Prior to this storm, there was a ~5 m high continuous primary dune ridge that spanned the entire island [2]. Similar to several other beach communities along the U.S. East Coast and in South Carolina [28], the Isle of Palms has tried to combat the effects of erosion with beach nourishment. In 2008, approximately 714,000 m³ of sand was placed on the northeast end of the island, which extended 3,100 m [28]. The longshore current direction is from the northeast to the southwest and it is approximately 6 km from the nourishment to the field site.

More recently, Hurricane Matthew (2016) first made landfall on the mainland of the U.S. at McClellanville, SC (45.3 km NNE of IOP) as a Category 1 storm [29]. This same region experienced the most severe Hurricane Hugo damage [2]. In Charleston, SC (8 km SSW of McClellanville), a 1.0–1.9 m (relative to MHHW) storm surge was measured [30]. It was fortunate that the storm arrived during the ebb tide. Approximately one year later (09/11/17), Hurricane Irma impacted the study region. Hurricane Irma made landfall in the United States in the Florida Keys as a Category 4 storm [31]. The storm did not directly make landfall in South Carolina, but in Charleston, a 15.0 m/s maximum sustained wind and 23.6 m/s gust was measured. A 0.5 m storm surge was measured (also in Charleston) and 193 mm of rain was recorded in McClellanville [31].

This study compares the geomorphic change at a dune system that has adjacent natural and mechanical dune sections. We focus this paper on three key dates, which are illustrated in Figure 3: (1) post-Hurricane Matthew and mechanical dune establishment survey: 10/28/16; (2) pre-Hurricane Irma survey (and maximum recovery condition): 09/07/17; (3) post-Hurricane Irma survey: (09/14/17). The entire study site length is 40 m, all of which is within the unstabilized inlet zone according to the

State's coastal management program [32]. There are approximately 40 m from the current setback line to the wet/dry line. The natural dune is 15.3 m long.

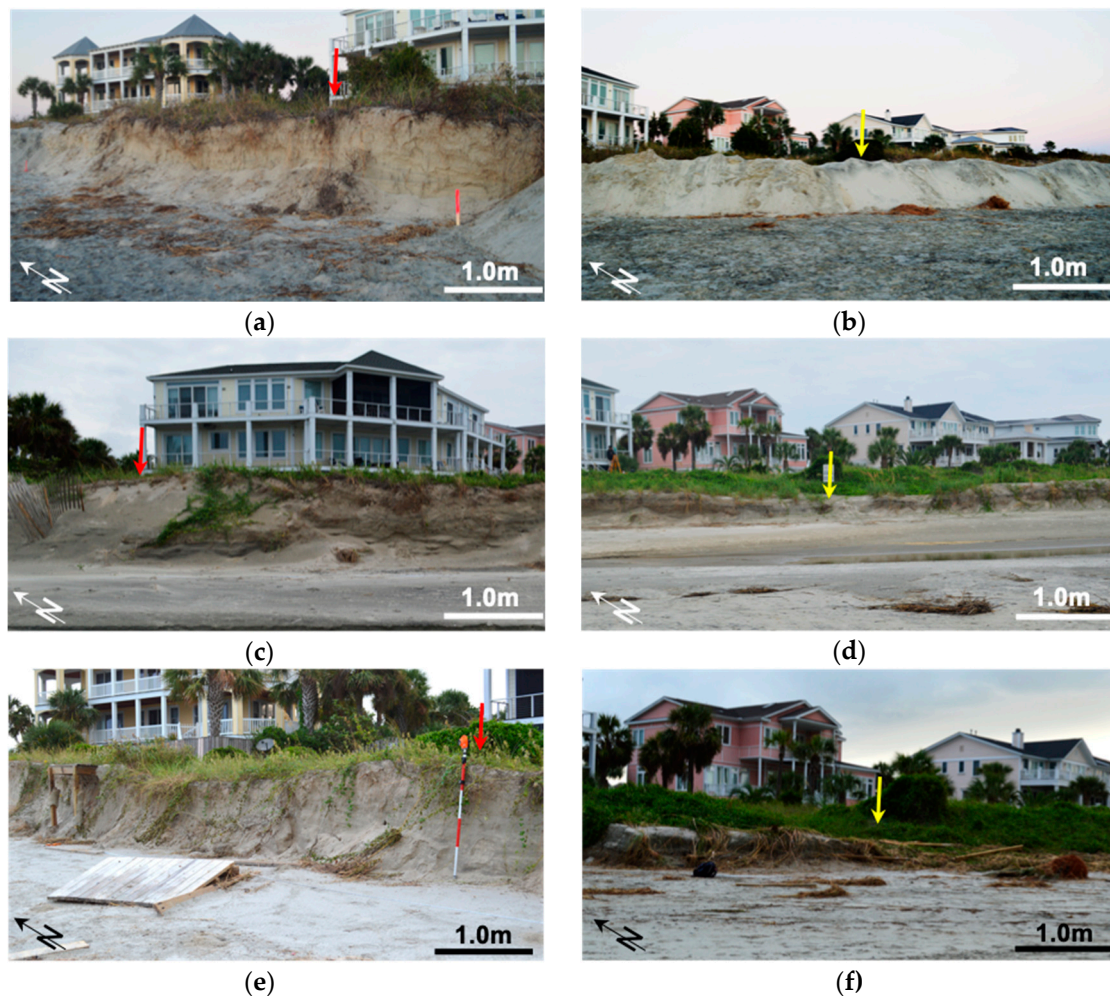


Figure 3. Images of the natural (a,c,e) and mechanical dune (b,d,f) following Hurricane Matthew shortly following the establishment of the mechanical dune (10/28/16; (a,b)), after approximately 10 months of recovery (09/07/17; (c,d)), and following the impact of Hurricane Irma (09/14/17; (e,f)) on 09/14/17. Colored arrows point to the same locations.

When the site was first surveyed on 10/28/16 (12 days after Hurricane Matthew), it was characterized by a substantial post-storm scarp (Figure 3a). Figure 3b shows the mechanical dune on 10/28/16 that was emplaced on 10/19/16 under the auspices of the emergency orders (issued on 10/04/16) to protect existing infrastructure. The scraping occurred directly adjacent to our natural site and extended approximately 1000 m alongshore, well beyond our study area. The scraped sand was placed along the former primary dune line. The site recovered for approximately ten months (Figure 3c,d). However, this recovery was truncated by Hurricane Irma because the devastation was so extensive (Figure 3e,f). Hurricane Irma prompted emergency orders to be issued again and the study area was scraped again. This second scraping event is beyond the scope of this paper, but it demonstrates the pervasiveness of this activity in South Carolina.

2.2. Field Methods

Geomorphic surveys were conducted on the natural and mechanical dunes on IOP approximately every 2–3 weeks. Data are presented for 11 months, bound by surveys directly following Hurricanes Matthew (10/28/16) and Irma (09/14/17). Surveys were conducted using a Sokkia Series 30R Total

Station. This instrument has an accuracy of ± 2 mm. Survey points were taken from the secondary dune to the water line along transects every ~ 1 m in the dune, ~ 3 m on the beach, and at geomorphic breakpoints. An average of 200 survey points were taken during each survey. Benchmarks were established using a X90-OPUS Static GPS receiver that has a ± 5 mm horizontal and vertical accuracy. Photographs document morphology and vegetation change. Surficial sediment samples were gathered from the swash zone, mid-beach, and dune five times during the study period (10/28/16, 05/05/17, 08/17/17, 09/07/17, and 09/14/17).

2.3. Data Analysis

2.3.1. Grain Size

Sediment samples gathered in the field were analyzed in the laboratory to obtain granulometry from the swash zone, mid-beach, and the natural and mechanical dunes. The samples were dried and split to obtain a randomized sample between 50–100 g. The randomized sample was processed using a standard Ro-Tap shaker for 10 min with quarter phi interval sieves.

Sieving results were analyzed using GRADISTAT [33] to calculate median grain size and sorting statistics. Sorting (σ_G) was calculated using the modified geometric Folk and Ward [34] equation. Lower σ_G values indicate the sample is more well sorted.

2.3.2. Forcing Events

Wind speed and wave height readings recorded every 12 hours were retrieved from NOAA's National Data Buoy Center (station 41004), which is located 73.41 km SSE from the field site. All readings were recorded, but only readings exceeding two standard deviations are considered forcing events. King tide data were obtained from South Carolina King Tide Initiative managed by SCDHEC-OCRM. King tides have the potential to cause substantial dune scarping [3].

2.3.3. Topographic Surveys

All survey points were used to generate digital elevation models (DEMs) and change maps. The base elevation of the survey averaged 1.60 m and ranged from 1.02 m to 1.97 m. The interpolated surface vertical accuracy of the DEMs is 0.85 m RMSE. The seaward extent of the study area was determined from the overlapping offshore survey extent, which varied based on tides. The most overlapping onshore line was the landward extent of the study area, which approximated the pre-Hurricane Matthew secondary dune crest. To calculate volume change, the DEMs were subdivided into beach and dune portions similar to the method of [35]. The beach-dune boundary was delineated based on the first survey date and held constant throughout.

Profiles were calculated using the 3D analyst stack profile tool within ArcMap to determine horizontal distance and elevation. The tool introduces new vertices along a transect to capture the stacked DEMs characteristics. Two transects were created, one at the natural dune and one at the mechanical dune. The transects started at the dune toe and ended at the base of the post-Matthew secondary dune.

3. Results

3.1. Grain Size

Table 1 shows the median grain diameter (D_{50}) and sorting statistics for each sand sample collected from the mechanical dune, natural dune, mid-beach, and swash zone. There is a substantial difference in D_{50} between the mechanical and natural dune. Over the pre-storm study duration, the median grain diameter increased over time. We posit the smaller grains left the dune system via aeolian transport. All collected and analyzed sediment samples are well sorted (Table 1).

Table 1. Grain size characteristics (median (D_{50}) and sorting (σ_G)) for the mechanical and natural dune, the mid-beach, and swash zone. Empty cells indicate that no sand samples were collected at that time and location.

Survey Date	Mechanical Dune	Natural Dune	Mid-Beach	Swash
<i>D_{50} (μm)</i>				
10/28/16	149.4	183.0	155.9	170.1
05/05/17	151.6	161.8	143.2	-
08/17/17	153.8	-	136.7	-
09/07/17	172.7	-	155.2	179.8
09/14/17	155.2	-	161.8	232.3
<i>Sorting (σ_G)</i>				
10/28/16	1.32	1.27	1.48	1.32
05/05/17	1.33	1.27	1.29	-
08/17/17	1.31	-	1.30	-
09/07/17	1.28	-	1.27	1.37
09/14/17	1.29	-	1.27	1.36

3.2. Forcing Events

During the 322-day study duration, the site experienced 65 king tides (Figure 4). These occurred approximately every 30 days except between days 52–178 (equivalent to 12/18–04/23). The wind and wave events (defined here as exceeding two standard deviations, which is the same threshold used by [36], occurred more frequently compared to the king tides. During the study period the average wind speed and wave height was 6.12 m/s and 2.71 m, respectively. The periodicity of the wave events roughly corresponds to the lunar tidal cycle, as they occur every ~14–28 days. There was a paucity of wind and wave events between during the early summer (days 225–293 or 06/09–08/16), with exception to the wind events on 07/23 and 08/05. The activity of all forcing agents at the end of the study (on day 316, or 09/08) corresponds with Hurricane Irma.

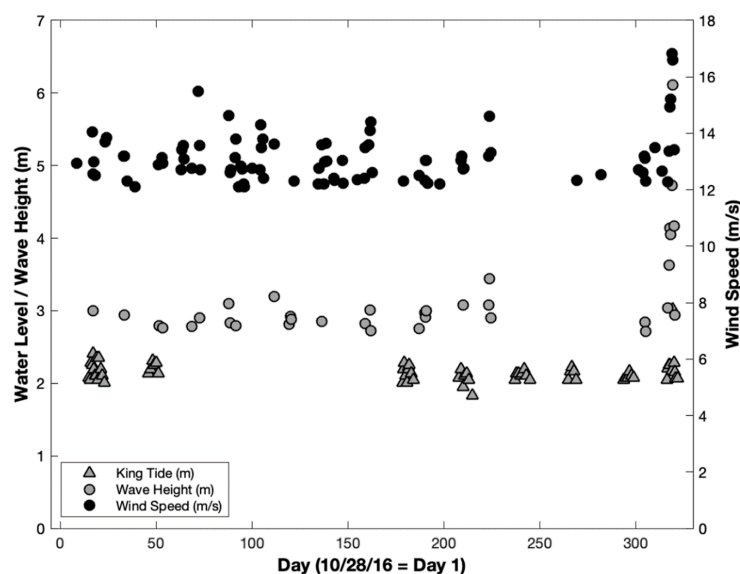


Figure 4. Forcing events (king tide and wave and wind events) observed at the Isle of Palms study site. All king tide events are shown. Only wave and wind events exceeding two standard deviations are displayed.

3.3. Topographic Surveys

Natural and mechanical dune volumes and areas are presented in Table 2. Dune areas are presented to demonstrate that volumetric changes are not correlated to the changing dune areas, except for the case of Hurricane Irma (discussed later). The normalized / standardized values in Table 2 are also presented in Figure 5 where values exceeding 1 indicate an increase from the initial (10/28) survey. In general, the erosion-accretion volumetric trend observed at the natural dune is also observed at the mechanical dune. On 11/30 and 03/04 the mechanical dune eroded while the natural dune accreted. The mechanical dune lost a substantial portion of its volume during the first two weeks (70%). Both dunes experienced a general increase of volume starting on 03/04. By 06/15, the mechanical dune exceeded its initial volume for the first time (by 16%) and it was on this date its normalized volume value exceeded 1. Regarding the natural dune, there were several instances (12/11, 04/15, and every survey following 04/15 until Hurricane Irma) where the volume exceeded the immediate post-Matthew condition measured on 10/28. Figure 5 clearly demonstrates that the natural dune is recovering more effectively, as the pre-Hurricane Irma average normalized volume values for the natural and mechanical dune are 1.29 and 0.71, respectively. The largest between-survey volumetric change resulted from Hurricane Irma (321 m³; Table 2), however, the change from 03/06-04/25 was comparable at 309 m³ (Table 2), but it was accretionary.

Representative DEM change maps are presented in Figure 6, which show the spatial variability of the accretion-erosion dynamics for the natural and mechanical dune. These DEMs are oriented so that the secondary dune is to the right of the dotted boxes. The recovery of the post-Hurricane Matthew dunes (prior to Hurricane Irma's impact) is shown in Figure 6a. The natural dune experienced net accretion, which was concentrated at the dune toe due to avalanching. In July an illegal sand fence was constructed on the avalanched sand. Also, around this time, the vegetation that started growing in the spring at the natural dune toe was at its peak, which promoted accretion (evidenced by the linear accretionary blue region within the dotted box). The NW to SE trending red (erosional) region is explained because this is the source sand for the avalanching. Early surveys of the natural dune (data not shown here) indicated the backdune area was stable, so we did not repeatedly survey this region. However, the DEM interpolation artificially and mistakenly created an accretionary lobe (colored blue) in the secondary dune.

Table 2. Area (m²) and volumes (m³) for the natural and mechanical dune. The dune area was delineated on 10/28/16 and held constant throughout the study period.

Survey Date	Study Date	Area (m ²)	Volume (m ³)	Area (m ²)	Volume (m ³)
<i>Natural Dune</i>			<i>Mechanical Dune</i>		
10/28/16	1	339.51	397.17	413.75	705.09
11/12/16	16	301.92	352.19	324.61	282.01
11/30/16	34	336.10	397.89	302.14	246.37
12/11/16	45	313.24	586.30	315.59	389.15
01/15/17	80	291.42	348.28	271.06	243.58
02/08/17	104	316.91	361.06	303.52	236.46
03/04/17	128	286.22	286.22	428.86	275.57
04/15/17	170	307.24	595.18	305.27	436.88
05/05/17	190	316.66	512.17	314.61	416.00
06/15/17	231	357.02	704.24	460.26	816.13
07/06/17	252	359.69	700.29	488.43	884.07
08/17/17	294	355.75	591.87	481.17	834.02
09/07/17	315	359.95	693.24	491.15	936.29
09/14/17	322	310.83	372.39	494.06	656.47

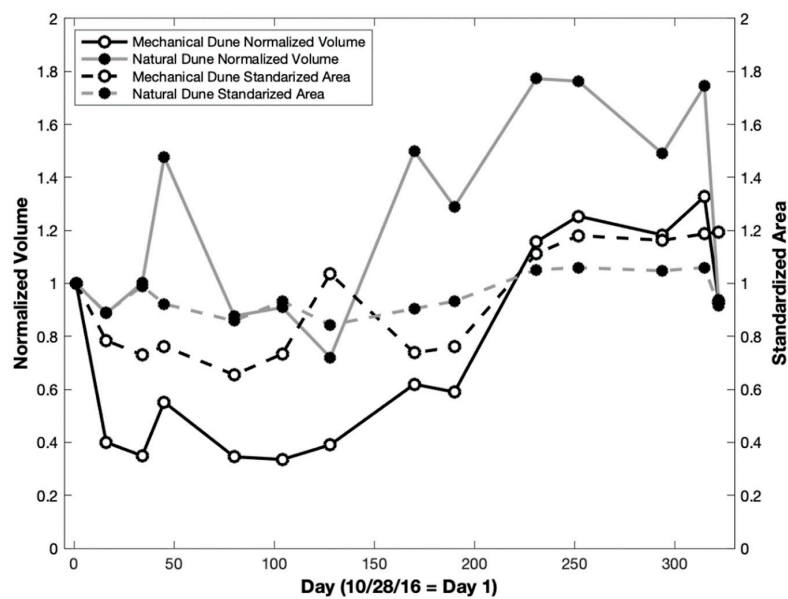


Figure 5. Normalized (according to the initial, 10/28/16, survey) volumetric change of the natural and mechanical dunes (left axis; solid lines) where values <1 and >1 indicate dune erosion and accretion, respectively. The standardized area values are calculated according to the 10/28/16 survey where values <1 indicate there is a reduction of initial dune area (right axis; dashed lines). The standardized area is presented because the dune area fluctuated each survey.

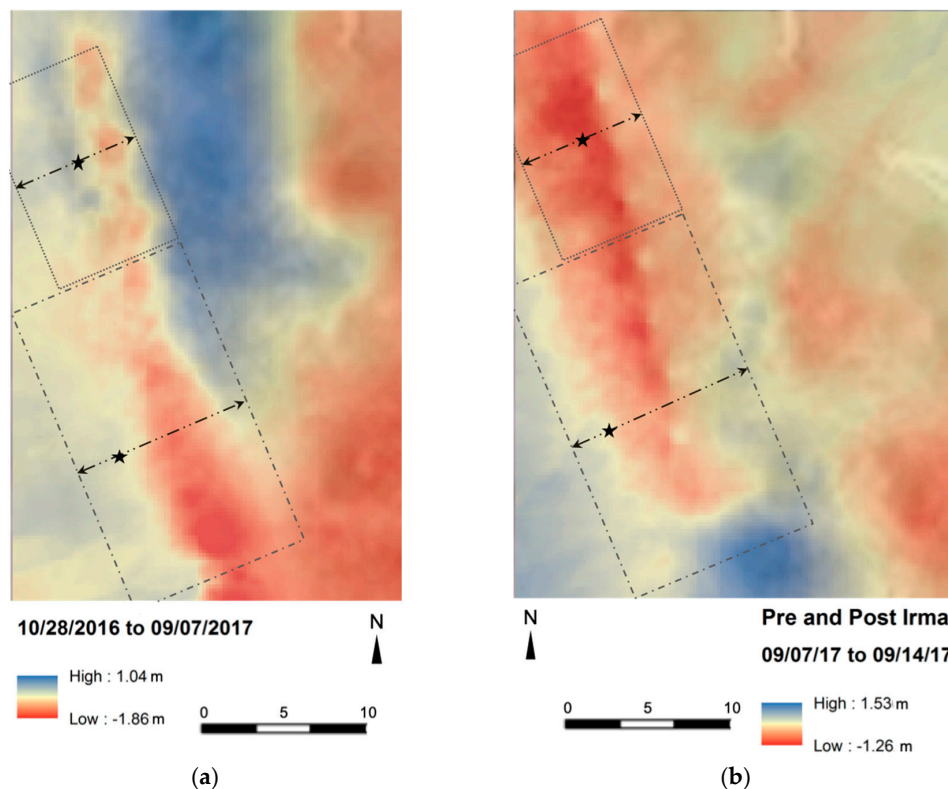


Figure 6. DEM change maps where red and blue hues show erosion and accretion, respectively. The secondary dunes are to the right of the dotted boxes. The mechanical and natural dunes (according to the 10/28 survey) are delineated by grey dotted and dash-dotted boxes, respectively. Black stars show the location of the onshore side of the dune toe. (a) Change from 10/28 to 09/07 represents the recovery following Hurricane Matthew. (b) Change from 09/07 to 09/14 isolates the change from Hurricane Irma. The locations of the profiles (see Figure 7) are designated by the black dashed-dotted arrows.

The evolution of the mechanical dune post-Hurricane Matthew and prior to Hurricane Irma's impact is shown in Figure 6a within the dash-dotted box. There was substantial deflation of the mechanical dune—almost 2 m. The mechanical dune had scant vegetation on the dune crest (c.f., Section 4). Some Hurricane Matthew wrack remained seaward of the dune toe for almost the entire study duration shown in Figure 6a, which promoted some accretion. The accretion in the eastern side of the boxes (largely comprises the mechanical dune sand transporting onshore via aeolian mechanisms).

Figure 6b demonstrates the erosive effect of a hurricane on a natural and mechanical dune. The natural dune was wave-cut. The scarping extent was influenced by the vegetation and is visible in Figure 6b by the transition from dark to light shades of red. The storm surge overtopped the artificial dune and removed almost all evidence that a mechanical dune was ever present (see Figure 3b,f). The post-Irma dunescape was fairly homogenous in that there was no demarking line between the natural and mechanical dune. The exception to this was a storm-generated depositional lobe shown at the bottom of Figure 6b. Field observations suggest a large portion of this sand originated from the mechanical dune and it was transported by water during the storm.

DEM-based profiles extracted at the approximate midpoint of the natural and mechanical dunes are shown in Figure 7a,b, respectively. We present the three key dates, which allow us to highlight: 1) the Hurricane Matthew recovery using data following Hurricane Matthew (2016) to just prior to Hurricane Irma (10/28-09/07); and 2) the impact of Hurricane Irma using pre and post-Hurricane Irma data (09/07-09/14). During the ~10 months following Hurricane Matthew (10/28-09/07), the natural dune (Figure 7a) mainly accreted. The landward migration of the mechanical dune is evident in Figure 7b. Also visible on the mechanical dune profile (Figure 7b) is the shoreface erosion/deflation (see distances 0-2 m). Similar to the DEMs (Figure 6), the substantial erosion associated with Hurricane Irma is evident in the dune profiles (Figure 7). Hurricane Irma resulted in approximately 4 m and 2 m of landward dune erosion at the natural and mechanical site, respectively. The natural dune was scarped.

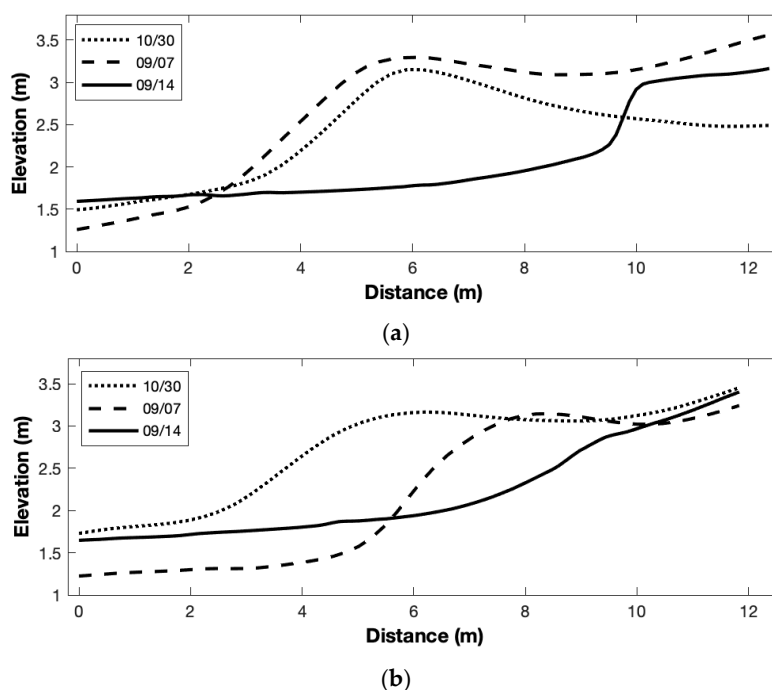


Figure 7. Topographic profiles from the mechanical and natural dune obtained during the first survey (10/28), the most recovered profile, which is also the pre-Hurricane Irma survey (09/07), and the post-Irma (09/14) survey. Representative profiles are shown from the natural (a) and mechanical (b) dunes. The elevation information for the profiles were obtained from the DEMs created for each survey.

4. Discussion

Given a mechanical dune median grain diameter of $156.6\ \mu\text{m}$ and using the equation of [37], the estimated threshold shear velocity is $0.17\ \text{m/s}$. During the study period, wind speeds $10\ \text{m}$ above the surface averaged $6.1\ \text{m/s}$; the $>2\sigma$ events averaged $13.1\ \text{m/s}$. Using Prandtl-von Kármán's Law of the Wall equation and average $>2\sigma$ wind conditions, shear velocity is estimated as $0.24\ \text{m/s}$, which exceeds the threshold for aeolian sand transport. This calculation assumes 'ideal' conditions (c.f., [38]), which also assumes dry sand. Starting in late January (around day 88) we started to observe centimeter-scale surficial ripples and a shell veneer from the removal of the finer sand grains on the mechanical dune (the latter being similar to [13]). Between study days 88 and 125, the conditions were conducive to aeolian transport, as there were only 12 total hours of scattered rain showers and several instances of $>2\sigma$ events (Figure 4). These favorable transport conditions support the onshore deposition of mechanical dune sand that was observed. The constructed shape of the Isle of Palms mechanical dune also encourages increased transport rates, similar to [13,15].

The natural dune system was accreting (recovering) post-Matthew in the ~ 10 months following the storm, its volume increased by 75%. The artificial dune also accreted 32% during this period. Both dune systems experienced general growth starting in March (day 125; Table 2). This timing corresponds to the increased growth of new vegetation, predominately at the natural dune site. Figure 8 shows a series of images in the spring (a: 03/25; b and c: 04/15; d and e: 05/05) from the natural and mechanical dune to highlight the difference in vegetation recolonization between sites (note, we obtained images on 03/25 and did not conduct a topographic survey). In panels a, b, d (Figure 8), the post-storm vegetation is brighter green and is located seaward of the natural dune. No post-storm vegetation was present on the mechanical dune on 03/25 (Figure 8a). On 04/15 and 05/05, we observed a limited amount of new growth of dune grasses on the crest of the mechanical dune (Figure 8c,e). We suspect that the reduced density, differing location, and species type of vegetation at the mechanical dune (also observed by [1] at a scraped site) not only limited accretion, but also warrants additional investigation. Previous studies [39,40] observed the elimination of species when a threshold of survival is crossed due to plant burial. These studies and this our observations relating dune recovery to vegetation suggest a disadvantage to scraping is species burial, which inhibits regrowth.

The comparison of forcing events and volumetric change (Figure 9) suggests that the wave and wind events exceeding $>2\sigma$ and king tide events (i.e., those designated by the green lines) during this study period (with exception to Hurricane Irma) did not strongly influence the erosion-accretion dynamics. A powerful nor'easter (colloquially referred to as Winter Storm Stella) impacted the study site in the days directly following our March survey (03/10-03/18). Despite the above average wind conditions, the natural and artificial system experienced accretion in the one month time span before the next survey. The magnitude of this accretion is roughly equal to the erosion experienced from Hurricane Irma.

During Hurricane Irma, the mechanical dune eroded 30% and the natural dune eroded 47% (Table 2; based on volume). However, during Hurricane Irma the natural dune area decreased 14% while the mechanical dune area increased. Therefore, we posit the reported volumetric changes should be thought of as closer to equivalent for both sites (given a normalized area). The shape of both dunes prior to the storm also influenced the erosion magnitude. The natural dune was scraped, causing most of the dune sand to deposit on the shoreface. The artificial dune was overwashed causing the dune sand to splay landward and to the south (see blue colored accretionary deposit in Figure 6b) and allowing the dune sand to stay in system (i.e., within our volumetric measurement area).

The natural and mechanical dunes were adjacent to each other. This arrangement was advantageous because the forcing mechanisms were the same. However, the limitation was that mechanical dune sand also leaked into the natural dune study area. The accretion shown at the bottom of the natural dune box in Figure 6a comprises mechanical sand and 'natural' accretion. Another minor data limitation is the impact of humans. Signage clearly indicates not to walk on the dunes, but people ignore that, especially on the mechanical dune. These 'human erosion machines' (HEMs) trample vegetation and discourage recovery.

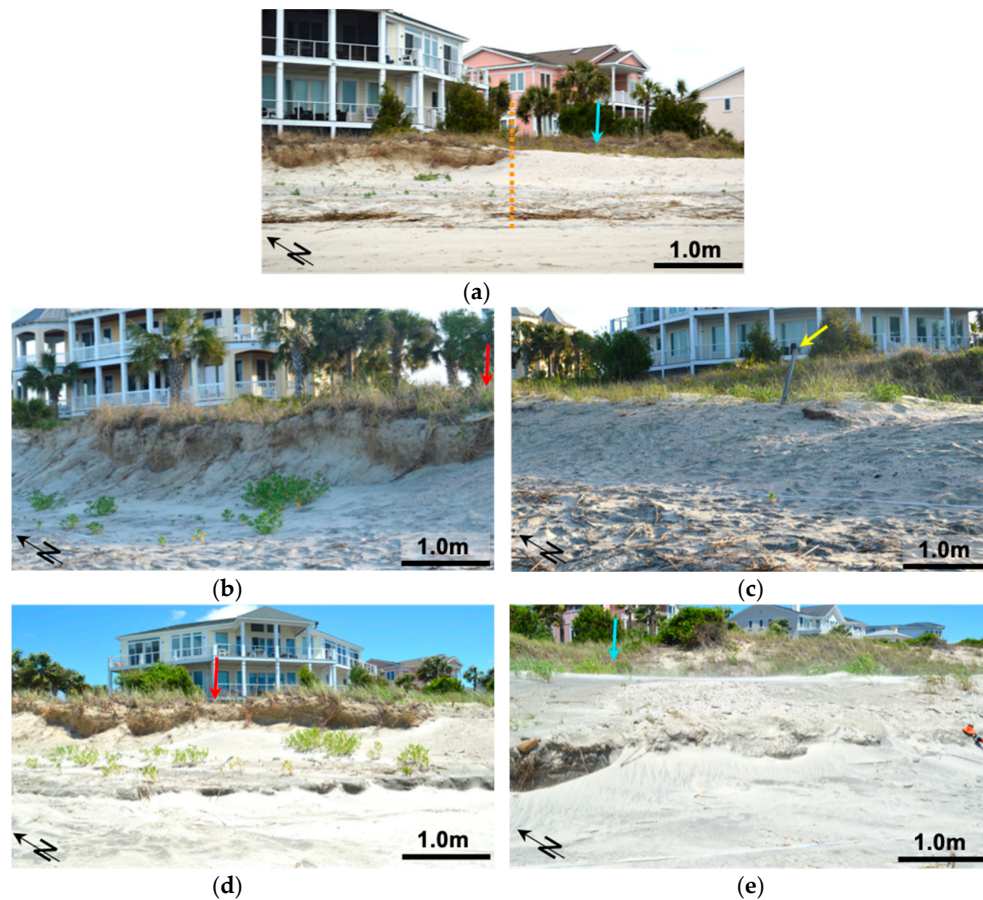


Figure 8. Images of the natural (a,b,d) and mechanical dune (a,d,e) on 03/25 (a), 04/15 (b) and (c), and 05/05 (d) and (e). In (a) the natural (left) and mechanical (right) dunes are delineated by the orange dotted line. Colored arrows point to the same locations and are coordinated to the arrows in Figure 3.

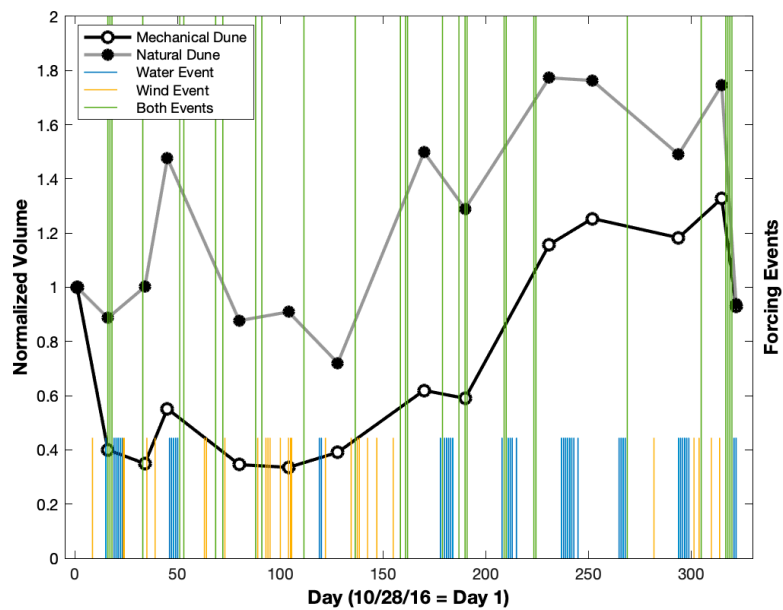


Figure 9. Normalized mechanical and natural dune volumes (also shown on Figure 5) plotted with forcing agents (also shown on Figures 4 and 6). The forcing agents are vertical lines where the orange and blue colors indicate wind and water (wave or king tide) events, respectively, and the green lines demark when a king tide, wave, and wind event occur concurrently.

5. Conclusions

This study considered coastal morphology and the magnitude and frequency of forcing agents (wind and wave events and king tides) to compare the performance of mechanical (scraped) and natural dunes over approximately one year. Specifically, this research investigated a natural and an unvegetated scraped dune that was emplaced along the South Carolina coast immediately after Hurricane Matthew as a mitigation effort to protect against the king tide flooding expected the following week. The amalgamation of results suggest that scraping is not a year-long solution and emphasize the importance of anchoring the sand, preferably with vegetation. The coast of South Carolina has been impacted by substantial tropical storms annually from 2015–2018, so year-long studies, such as this, may be the most applicable temporal research and planning window for scientists and managers, respectively.

This study focused on three key dates: (1) post-Hurricane Matthew and mechanical dune establishment survey: 10/28/16; (2) pre-Hurricane Irma survey (and maximum recovery condition): 09/07/17; (3) post-Hurricane Irma survey (09/14/17) to assess the dunes' recovery and physical resiliency. During the recovery phase (10/28/17–09/07/17), the volumetric increases of the mechanical and natural dune were 32% and 75%, respectively. These findings, which were based on approximately one year of data, suggest that scraping alone is not the ideal protection method. If scraping is employed, we advocate that the dune should be augmented by planting. Ideally, the storm-impacted dune should naturally recover.

Post-storm vegetation regrowth varied around the mechanical and natural dune, which encouraged aeolian transport on the mechanical dune and subsequently its deflation. We observed that at this study site, the main control on volume is vegetation compared to non-extreme forcing events. The placement of the scraped sand stifles the vegetation (re)growth, (c.f., [41] for discussion on burial-tolerant and -intolerant species).

Hurricane Irma (2017), an extreme forcing event, substantially impacted the dunes. The natural dune was scarped, the mechanical dune was overtopped, and the system was essentially left homogeneous. This single event caused erosion that was roughly equivalent in magnitude at the natural and mechanical dune sites.

The results from this study question the current practice of sand scraping along the South Carolina coast, which occurs post-storm, emplacement along the former primary dune line, and does not require the planting of vegetation. It is recognized that this study considered one portion of the coast and the study duration was approximately one year. Additional research with a larger spatial extent and longer temporal duration that quantitatively assesses vegetation is forthcoming. This work is relevant to many developed coasts, especially with increasing trepidation to employ hardened management techniques.

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